DYNAMIC PAVEMENT LOADS MEASURED FOR A VARIETY OF

TRUCK SUSPENSIONS

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ABSTRACT

All vehicles bounce as they travel along a road.   This increases the loads applied to the road and hence road wear. Some types of suspension bounce more than others. The dynamic loads on roads and bridges have been measured for a rigid truck and a number of articulated goods vehicles. Measurements were made on the TRRL track, on public roads and on a number of bridges at speeds of up to 96 km/h. Semi-trailer bogies produce relatively higher dynamic load factors than tractor drive axles. Air suspensions almost always produce lower dynamic loads than do other types. Dynamic loads under steel leaf suspensions increase with speed more than do loads under air suspensions. The implications for road wear are considered and the possibility of rating suspensions for road wear potential is discussed.

1   INTRODUCTION

All vehicles bounce as they travel along any road. On heavy goods vehicles this bouncing causes vibration at the driver's position and the load bed, and continuous variation of the loads applied to the road surface by the vehicle wheels. This paper is concerned with the effect of different types of suspension on the loads applied to roads and bridges by heavy goods vehicles, and the effect of these dynamically varying loads on road wear.

Measurements of dynamic road loads under heavy goods vehicles were made during the 1960's by Mitschke (1961), Potter (1968) and Whittemore et al (1970). Whittemore et al measured dynamic road loads for three types of suspension travelling over roads of various roughnesses at two different speeds. Potter used road-mounted instrumentation to measure dynamic wheel loads for two rigid goods vehicles, two agricultural tractors, a dumper and a grader running over a 40 mm plank on a track. During the 1970's Page (1976) measured the peak dynamic axle loads under a 2-axle goods vehicle crossing many different bridges. He showed the the largest dynamic loads occurred near the ends of the bridges and that the maximum dynamic axle load was 1.8 times the static axle load. This "dynamic load factor" of 1.8 is used in Britain in the design of road bridges.

During the late 1970's and early 1980's Sweatman in Australia and Mace in Britain measured dynamic loads under heavy goods vehicles on public roads (Dickerson and Mace, 1981; Sweatman, 1983; Mace and Stephenson, 1989). These measurements showed that the dynamic road loads caused wheel load variations that were usually a modulated sinusoid with a dominant frequency of 2-5 Hz. Their distribution was Gaussian and the standard deviation, which depended on speed, road roughness and type of suspension, was typically 10-30 percent of the static wheel load. Sweatman showed

that under given conditions walking beam suspensions caused higher dynamic loads than steel leaf springs, while air springs and torsion bar springs caused lower loads.

During the 1980's measurements in Canada (Woodrooffe and Leblanc, 1986), Germany (Gorge, 1984; Eisenmann and Gauss, 1985) and Britain (Addis et al, 1986) showed that strains in road pavements and in the soil under a road were directly proportional to the dynamic wheel loads applied to the pavement immediately above the strain gauges. This meant that it is only necessary to measure the dynamic wheel loads applied to the pavement to estimate the road wear and fatigue damage that they cause. Further German measurements (Hahn,1987) confirmed Sweatman's observations of the effects of different types of suspension. Hahn studied 1-, 2- and 3- axle groups and, for the single axles, examined the effects of spring stiffness and dampers on dynamic loads.

This paper is concerned with recent measurements by TRRL of dynamic loads under goods vehicles on the TRRL test track and on a number of bridges on public roads. The vehicles are a two axle rigid and a variety of 4 and 5 axle articulated goods vehicles. The bogies of the semi-trailers include steel leaf, air and rubber suspensions. The tractor used for the first measurements has a steel leaf suspended drive axle, and measurements using an air-suspended tractor are scheduled for Spring 1989. These measurements extend those of Sweatman and Hahn, and particularly study dynamic loads on bridges as well as roads.

2   OUTLINE OF THE TRRL TEST PROGRAMME

The TRRL test programme is designed to determine the difference in road wear caused by different suspensions and to develop a test to rate the "road friendliness" of different types. This involves measuring dynamic loads under a wide range of suspensions in carefully selected conditions. In the TRRL programme each suspension is tested with the vehicle fully loaded and unloaded. Each test consists of measurements at 20, 30, 40, 50 and 60 mph (32, 48, 64, 80 and 96 km/h) on rough, medium and smooth sections of the TRRL research track. The tests on the smooth or medium sections are repeated to include running over a 25mm (1 inch) plank to simulate a bridge expansion joint or a pothole. A further series of measurements are made at speeds of 40-60 mph (64-96 km/h) over six bridges on the local motorway and trunk road network. These are to establish the peak dynamic loads at the abutments and expansion joints on real bridges. Measurements are also being made at low speed (about 40 km/h) over six hump bridges to determine the quasi-static load transfer between axles on these bridges.

3 VEHICLES AND INSTRUMENTATION

The vehicles used are:

1) A Volvo F88 two-axle goods vehicle with steel leaf springs,plated gross weight 16,260 kg (35,850 lb). Because this vehicle was designed for hauling drawbar trailers the drive axle spring has many leaves and is exceptionally stiff.

2) A DAF 3300 two-axle tractor with steel leaf springs, used to tow the semi-trailers listed below.

3) A DAF F95 two-axle tractor with an air-suspended drive axle.

4) A 4-axle rigid tanker with an inverted steel spring suspension for the rear bogie.

5) A two-axle semi-trailer with monoleaf steel springs.

6) A two-axle semi-trailer with air springs.

7) A 3-axle semi-trailer with 3-leaf steel springs.

8) A semi-trailer with its suspension mounted on a removeable sub-frame so that different types can be fitted for testing. To date sub-frames have been obtained with 2-axle steel monoleaf springs, three types of 2-axle air suspension, a 3-axle air suspension and a rubber-sprung walking beam.

All the semi-trailers are about 12 m long. The 4-axle articulated vehicles are plated to 32,520 kg (71,690 lb) and the 5-axle vehicles to 38,000 kg (83,780 lb).

All vehicles except number 4 are instrumented to measure all wheel loads (half-axle loads) simultaneously (on vehicle 4 only the rear bogie was instrumented). This is done by strain gauges to measure the bending of the axles between the suspension and the hub, plus accelerometers to correct for the vertical inertia loads due to the unsprung mass outboard of the strain gauges. Signals from these sensors are recorded on analogue magnetic tape. The position of the vehicle along a test section is determined by counting revolutions of the prop-shaft. The start of the test section is marked by a strip of reflective tape on the road which returns a light beam to a photocell under the vehicle. This system locates the vehicle on the test section to an accuracy of about 10 cm. The load measuring instrumentation is probably accurate to 3 percent at 3 Hz and 5 percent at 15 Hz, although this has not yet been formally established.

4 RESULTS

4.1 Dynamic loads on roads

The measured dynamic wheel loads show many of the features noted in earlier reports. On smooth roads the main dynamic effect is the whole vehicle bouncing on its springs and tyres at 2-4 Hz. The dynamic loads on all the axles are in phase and, because there is usually little pitching in the motion, the amplitudes of the dynamic loads on the different axles are similar. This mode of vibration is called "heave" (in the USA "jounce"). At particular points of road roughness such as a pothole, bridge expansion joint or a plank on the test track, the individual axles oscillate vertically at 10-15 Hz with very little motion of

the sprung mass.   This vibration mode is called "wheel hop"   (in
the USA "axle tramp").

Figure 1a shows the measured load under a wheel of a steel leaf
sprung semi-trailer bogie on the TRRL track.   The 3 Hz heave mode
can be seen clearly,   causing the wheel load to vary between 2.3
tonne and 4.7 tonne.   At 35 m the wheel passes over a 25 mm plank
which causes wheel hop and the load oscillates between 0.9 tonnes
and 6.0 tonnes at about 12 Hz.   The section of the TRRL track
used has the roughness of a typical motorway, so the amplitude of
the 3 Hz heave mode is typical of that in service on a good road.
Traces for successive test runs at the same speed show that the
dynamic load repeats very accurately,   even during the wheel hop
motion after the plank.

Figure 1b shows the similar trace for the dynamic load measured
for an air sprung semi-trailer. There is noticeably less heave on
the air sprung bogie and the wheel hop motion at the plank shows
a larger amplitude and more cycles of oscillation (the damping
can be measured as 10 percent critical).

Figure 1c shows the corresponding trace for a rubber sprung
bogie.   The maximum peak dynamic load factor is even higher than
for the air suspension and there are more cycles of high
amplitude vibration.   The decay of the wheel hop vibration is
complex, perhaps reflecting the pitching of the bogie beam.

The principal results from the dynamic load measurements on
reasonably level roads are summarised in Figures 2,   3 and 4,
showing the variation with speed of the dynamic load coefficient
(the standard deviation of the dynamic load divided by the static
load on the wheel or axle) for drive axles,   2-axle bogies and 3-
axle bogies on rough, medium and smooth surfaces.   Each figure
gives results for all the types of suspension on one of the
sections of the TRRL track.   It is clear that the dynamic load
coefficient (dlc) increases with speed for the steel and rubber
suspensions more than for air.   The dlc increases more with road
roughness for air than for steel or rubber suspensions. At almost
any speed and roughness,   the dlc for the air suspensions is
lower than that for the steel suspensions,   while in most
circumstances rubber suspensions give higher dynamic loads than
steel.

Figure 5 shows the spectral density of the dynamic loads for
typical steel,   air and rubber sprung semi-trailer bogies on the
medium roughness section of the TRRL track.   These show that for
the air suspension a higher proportion of the vibration energy is
in the wheel hop mode than the heave mode,   while the reverse is
true,   and at much higher levels of energy,   for the steel sprung
bogie.   The rubber sprung bogie responds strongly at both
frequencies.

Figure 6 shows the responses of the three types of bogie
suspension to a 25 mm plank, in terms of the variation with speed
of the maximum and minimum peak dynamic load of the wheel ·hop
motion after the plank.   For all the suspensions the peak dynamic·
load increases with speed.   This increase is slightly greater for
the steel suspension than the air,   while the rubber shows a more

complex change with speed. The maximum dynamic factors measured are comparable to those measured on motorway bridges by Page (1976) and on a rough section of a test track by Hahn (1987).

4.2 Peak dynamic loads on bridges

Page (1976) showed peak dynamic loads on bridges of up to 1.8 times the static load at 40 mph (64 km/h). Dickerson and Mace (1981) showed peak loads on public roads of up to about 1.8 times static, again at 40 mph. Hahn (1987) has measured peak loads per km of up to twice static for steel leaf sprung 3-axle semi-trailer bogies at 50 mph (80 km/h), but lower values (about 1.65 times static) for air sprung axles.

The TRRL has measured peak dynamic loads on a small number of motorway bridges to compare with the peak transient loads measured at planks on the TRRL track. The bridges selected are not producing particularly high dynamic loads; the largest dynamic factor measured to date has been about 1.67 for a 2-axle steel sprung bogie. The corresponding peak dynamic load factor for an air sprung bogie on the same bridge was 1.22, and for a 3-axle steel sprung bogie 1.45. On all the bridges used for dynamic load measurements the peak loads were substantially less under the air suspended bogies than the steel sprung bogies. Figure 7 shows load histories for three semi-trailer bogies crossing one bridge on the M4 motorway. On this particular bridge,all three bogies show response in both the low frequency heave mode and the high frequency wheel hop mode. The difference in dynamic loads for 2-axle air, 2-axle steel and 3-axle steel sprung bogies is clear.

Although the maximum peak dynmaic load factor on the motorway bridges tested by Page (1976) was 1.8, about 80 percent of the bridges gave rise to peak dynamic load factors of less than 1.50 for a steel sprung axle. The differences in the peak dynamic loads . for different suspensions observed in practice on bridges do not appear in the tests over the 25 mm plank on the track. On the other hand, the plank test produces peak dynamic loads that are typical of the maximum peak loads measured by Page (1976) and Hahn (1987). Further work is needed to determine a profile to attach to the surface of a test track to generate a representative peak dynamic load for each type of suspension.

4.3 Interaction between semi-trailer and tractor

Measurements with the leaf steel sprung tractor towing a wide variety of semi-trailers shows that the dynamic loads on the tractor drive axle are not affected by the semi-trailer suspension. This is important, because it means that the suspension for the tractor drive axle does not have to be matched to a particular semi-trailer; one that is satisfactory for one semi-trailer appears likely to be satisfactory with all semi-trailers. It is not yet possible to know whether changing the tractor drive axle suspension affects the semi-trailer axle loads. This will be determined from the tests with an air sprung tractor that are scheduled for Spring 1989.

4.4 Features of a "road friendly" suspension.

It has been shown that dynamic axle loads are higher for leaf steel sprung semi-trailer bogies than for the steel sprung drive axle of the tractor. Hahn (1987) has found similar results. This suggests that, relative to semi-trailer bogie axles, drive axles cause less road wear than their higher static weight would imply.

Research in Germany has identified a number of suspension features that reduce road wear for a given static axle weight. These include a low heave stiffness to give a bounce frequency of less than 1.5 Hz, more than 25 percent critical damping, low friction, twin tyres and low tyrepatch contact presure (von Becker,1985). Results from the TRRL test programme suggests that to reduce the dynamic load coefficient on a semi-trailer axle to that of a drive axle requires the heave stiffness of the suspension to be considerably reduced. This would cause unacceptable roll flexibility unless an anti-roll bar is fitted. This can be achieved by the use of a trailing arm suspension to which the axle tube is clamped, which permits a low heave stiffness and a high roll stiffness. In addition, the trailing arm layout produces a suspension with low friction and stiction. As well as low friction and low heave stiffness, a road friendly suspension needs sufficient hydraulic damping and, if possible, low unsprung mass. An air suspension can offer all these features except lower unsprung mass, and it should also be possible to develop a mechanical suspension to do the same.

4.5 Implications for road wear

The AASHO road test (Highways Research Board 1962) showed that on average road wear is proportional to the sum of the fourth powers of the axle loads applied to a road. If high dynamic axle loads are distributed randomly along a road then the increase in road wear, Eisenmann (1975) have shown that the "dynamic pavement wear factor" is given by:

$$\text{dynamic pavement wear factor} = 1 + 6(dlc)^2 + 3(dlc)^4 \qquad 1.$$

Figure 8 shows the dynamic pavement wear factor for a number of suspension types and axle locations, deduced from measurements on the medium roughness section of the TRRL track. This is a good way to illustrate how much extra road wear is caused by dynamic loading, and how much wear can be reduced by using one type of suspension rather than another.

The previous paragraph assumes that high dynamic loads are randomly spread along a road. If high loads tend to cluster at particular points then their effect on wear at those points will be much higher than equation 1 suggests, with a local dynamic pavement wear factor of at least $(1 + dlc)^4$, or approximately $(1 + 4(dlc) + 6(dlc)^2)$. An analysis technique which appears promising is to use dynamic load measurements on a vehicle to derive the loads applied by each axle to a point on the road. These loads can be raised to the fourth power and summed to give

the total road wear, in standard axles, caused at that point by that vehicle. Repeating the analysis for a number of points along the road will show the difference in road wear from point to point. Repeating the analysis for different speeds will show whether at some speeds the peak dynamic loads on successive axles tend to be applied to the same points on the road (Cebon, 1987). It is hoped to test the technique in the next few months, using some of the TRRL axle load measurements.

Table 1 lists the proportion of structural road wear on British trunk roads and motorways that is caused by different classes of goods vehicle (Shane and Newton, 1988) and the amount this could be reduced by switching from steel leaf to air suspensions. It can be seen that over 70 percent of the road wear caused by trucks is caused by 4- and 5- articulated vehicles. (The proportion of 5-axle articulated vehicles has been increasing steadily since 1983 when their allowable weight was increased to 38,000 kg, but the 70 percent contribution to wear from large articulated vehicles has remained roughly constant.)

The increase in road wear due to dynamic bouncing has been estimated from dynamic load measurements by TRRL and by Hahn (1987). These suggest that if all steel leaf, rubber and walking beam suspensions could be replaced by air suspensions or their dynamic equivalents,then the wear due to drive axles could be reduced by 8 percent and that due to semi-trailer bogies by 10 – 20 percent. There are inevitably differences in the estimates based on the two sets of measurements because of detail differences in the vehicles tested, but the implications are similar and clear.

5   POSSIBLE SUSPENSION RATING TESTS

The research described above is showing clearly that some suspensions cause more road wear for a given static axle weight than do others. This finding has been used in Germany to allow buses whose suspension complies with the conditions outlined in Section 4.4 above (Tempo 100 conditions) to operate with higher drive axle weights. For heavy goods vehicles the task of defining a suspension rating test that realistically represents the road wear potential of a suspension is more difficult.

The TRRL tests have shown that there are four physical processes that define the axle loads for a given suspension under different circumstances. For all axles, single or multiple, it is low frequency bouncing that defines the dynamic loads on smooth roads, while the higher frequency wheel hop mode defines the peak transient load over an isolated rough element of a road such as a pothole. For multiple axle groups there is the degree of load equalisation between axles when the vehicle or trailer chassis is tilted (or when one axle is raised relative to the others). Also for multiple axle groups there is the shift in load between axles while crossing a hump bridge, and hence the peak axle load applied to the bridge. These processes are relatively independent (although there are clear links between the last two), and any suspension rating test procedure must exercise all four processes.

The 2 quasi-static processes of axle load transfer within bogies when trailers are tilted or pass over hump bridges are clearly best measured by tilting a trailer or driving it slowly over a specified hump. The peak dynamic load during the transient response to a particular element of road roughness such as a pot-hole or bridge abutment can be measured by driving the vehicle at a number of speeds over a small number of profile shapes fixed to the surface of a test track. The low frequency heave response to a smooth road must be measured at a number of speeds on one or a small number of sections of test track. These sections will need to be at least 400 m long to allow some 40 cycles of the heave mode to be observed and to reduce the statistical error of the measurement.

It is encouraging that the ranking of suspension types by dynamic loads on relatively smooth roads is not critically dependent on test conditions. In the TRRL tests the different suspensions usually rank in the same order regardless of road roughness or speed. However, both Hahn (1987) and Sweatman (1983) have shown that this is not always the case. Each author has examples of suspensions changing ranking as speed or road roughness is changed, as indeed do the TRRL tests (see, for example, the steel sprung 3-axle and the rubber sprung 2-axle bogies on the medium roughness section of the track, Figure 3). Despite this, the tests clearly categorise suspensions types causing high, medium or low dynamic loads. Changes in rank order with test condition tend to be within categories rather than between categories.

6   CONCLUSIONS

Measurements have been made of the dynamic loads under a large number of heavy goods vehicle suspensions at speeds of 32 to 96 km/h on smooth, medium and rough sections of the TRRL track, over planks laid on the track and over bridges on public roads.

At all speeds and on all sections of the track air sprung semi-trailer bogies produced lower dynamic loads than steel leaf sprung bogies, while rubber sprung bogies produced dynamic loads that were always higher than those for air bogies, and usually higher than those for steel sprung bogies. Three axle bogies usually produced lower dynamic loads than 2-axle bogies. Steel leaf semi-trailer bogies generated higher dynamic loads than steel leaf tractor drive axles, and this reduces the difference in road wear between lighter trailer axles and heavier drive axles.

The peak transient dynamic loads over planks on the test track are higher for air sprung axles than steel sprung axles, except at speeds of over 70 -80 km/h. Measurements on a small sample of bridges on motorways show smaller dynamic loads for air sprung than steel sprung bogies, but did not detect peak dynamic loads as high as those measured over a 25 mm plank on the test track. The measurements over the plank demonstrated peak dynamic loads that were comparable to the highest peak loads on public roads and bridges measured by other studies, but did not show the differences with suspension type in the peak dynamic loads on

bridges measured by TRRL.

The measurements show that loads applied to roads by heavy goods vehicles, and hence road wear, could be reduced significantly, perhaps by 10-15 percent, if all goods vehicles were fitted with suspensions with dynamic characteristics similar to the best used in the tests described.

The requirements for a test procedure to rate suspensions in terms of the potential for causing road wear are discussed.

7 ACKNOWLEDGEMENTS

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TABLE 1

(a) Road wear by category of goods vehicle
(total of surveys 1980-86)

Vehicle type	Percentage of vehicles %	Standard axles per vehicle* Standard axles	Percentage of road wear %
2-axle rigid	39.9	0.15	12.0
3-axle rigid	4.4	0.61	4.3
4-axle rigid	4.3	1.10	7.2
3-axle articulated	4.5	0.23	1.6
4-axle articulated	37.7	0.92	61.1
5-axle articulated	6.2	1.11	11.6
Others	3.0	0.55	2.0

*10 tonne standard axles

(b) Potential reduction in dynamic pavement wear at 90 km/h
medium roughness test sections

Axle/Suspension	Dynamic pavement wear factor ($\simeq 1+6.dlc^2$)		Wear saving, air instead of steel or rubber	
	TRRL	Hannover*	TRRL	Hannover
2-axle rigid, drive, multi-leaf steel	1.10	1.20	—	8%
tractor drive, steel leaf	1.07	1.20	—	8%
tractor drive, air or improved steel	—	1.10	/	/
trailer 2-axle bogie steel leaf	1.25	1.22	15%	14%
trailer 2-axle bogie rubber/ walking beam	1.19	1.33	11%	21%
trailer 2-axle bogie air	1.06	1.05	/	/
trailer 3-axle bogie steel leaf	1.14	1.38	9%	24%
trailer 3-axle bogie air	1.04	1.05	/	/
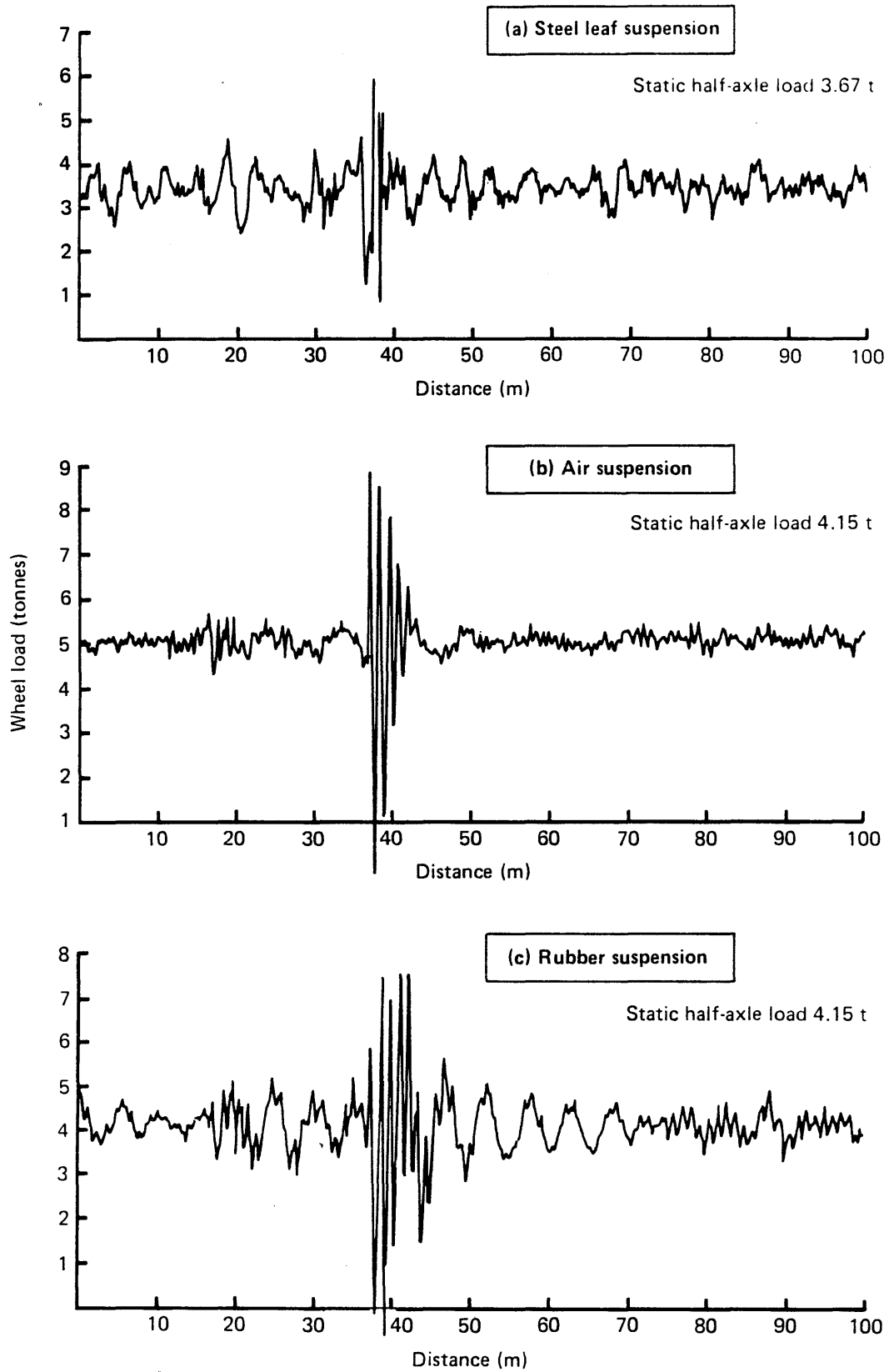
Fig.1 Dynamic wheel loads for three semi-trailer bogies at 48km/h on the medium roughness section of the TRRL track with a 25mm plank at 35m
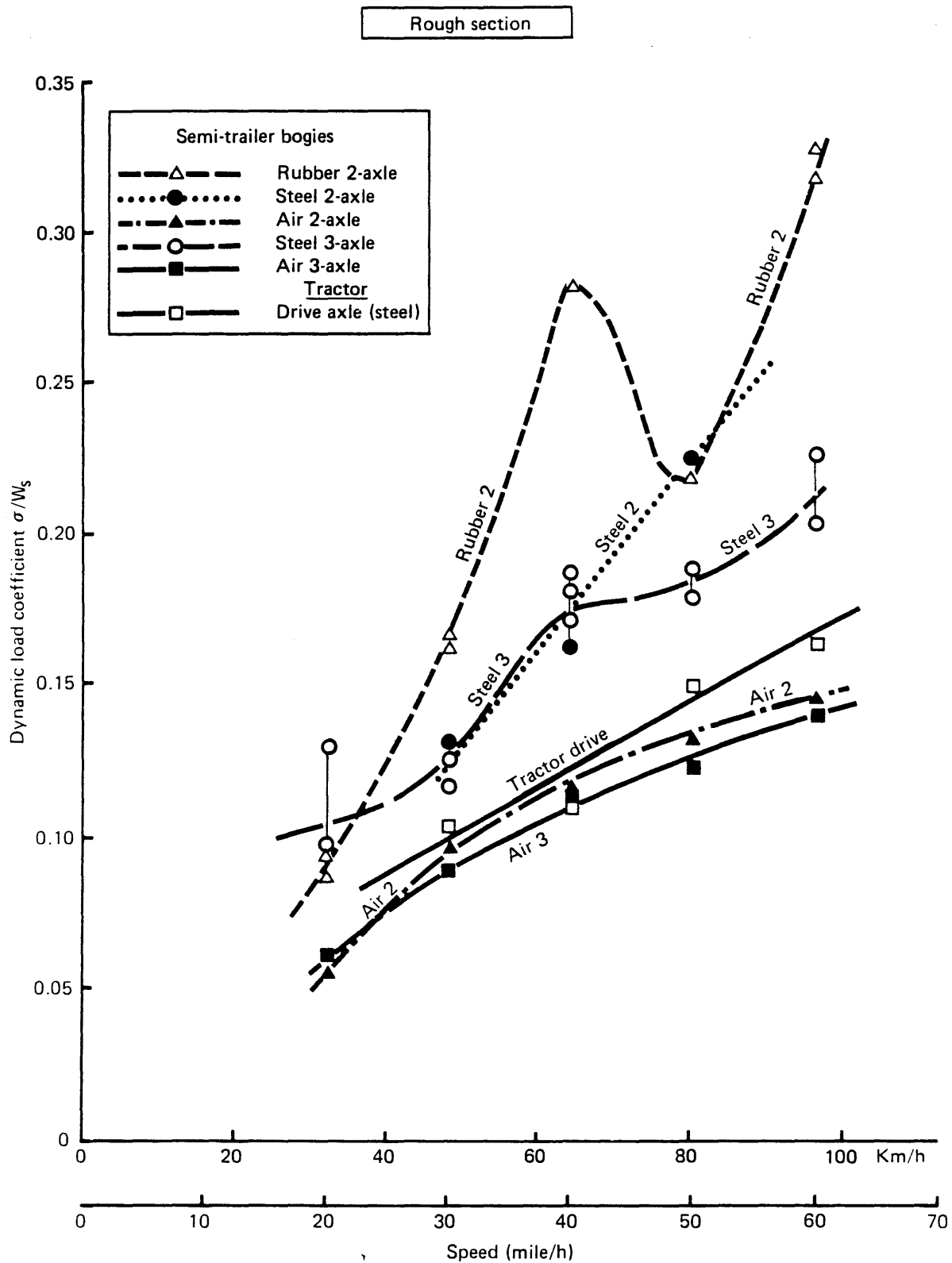
Fig.2 Dynamic load coefficients for the tractor drive axle and 2- and 3- axle
semi-trailer bogies on the rough section of the TRRL track.
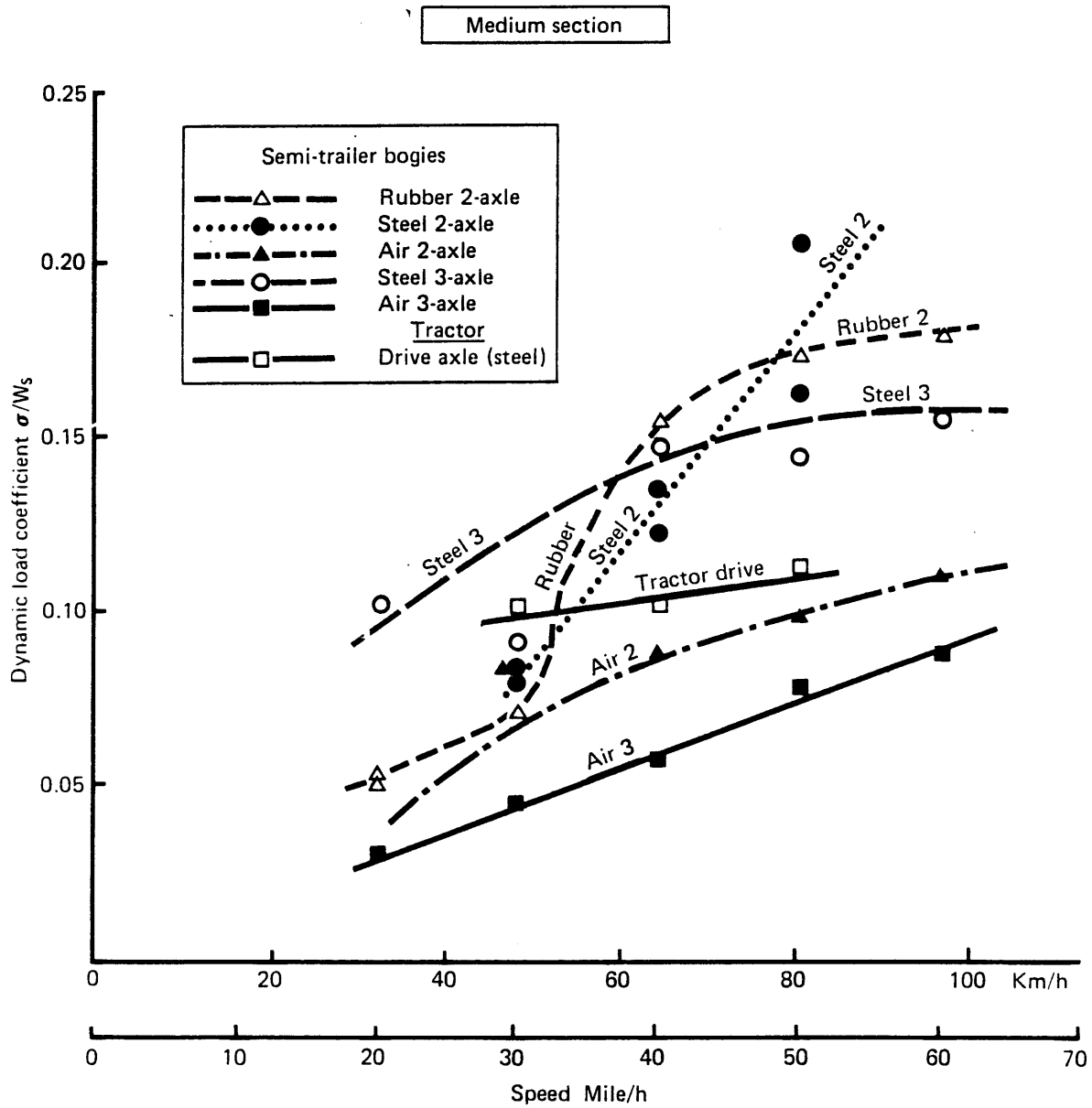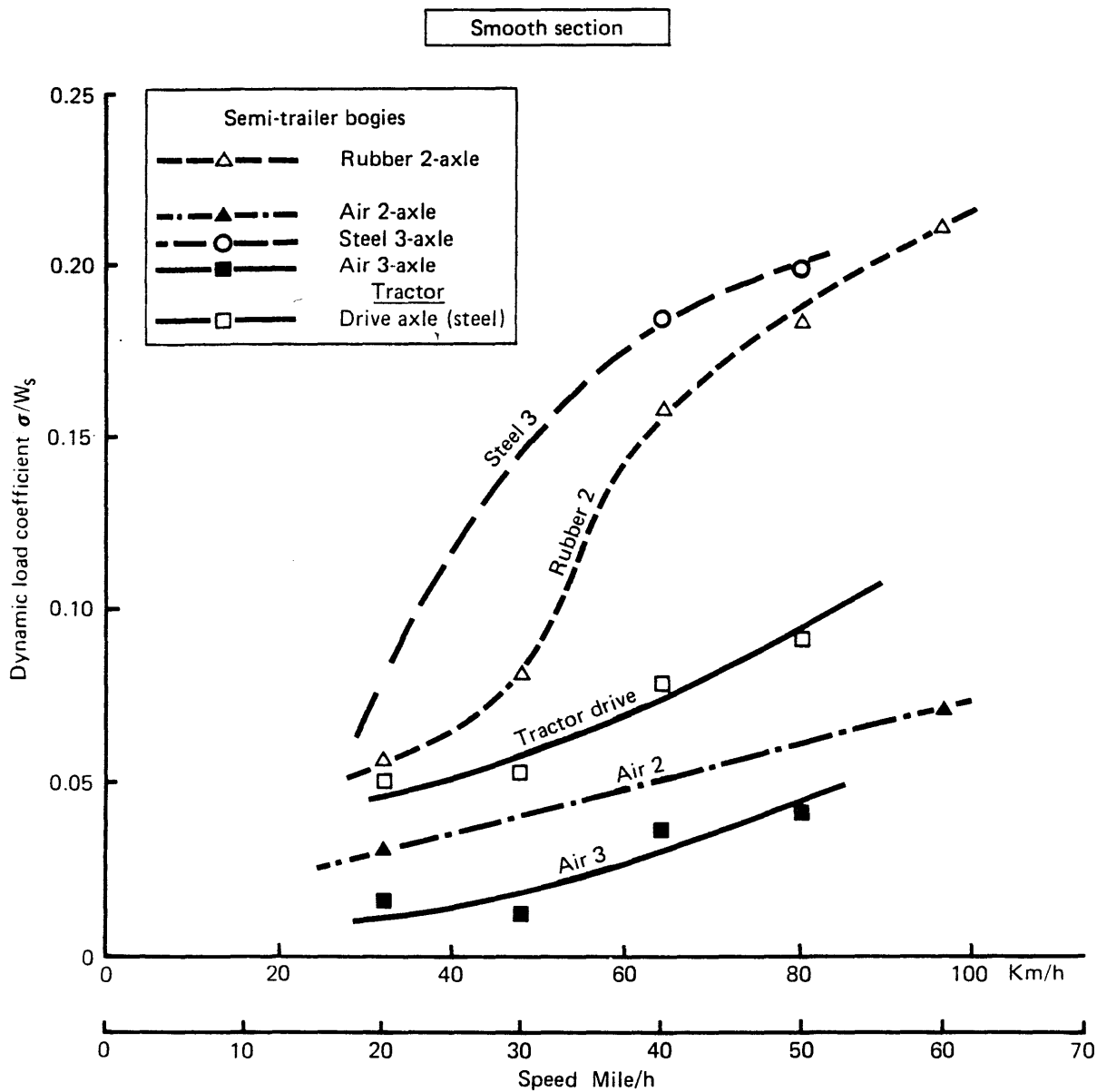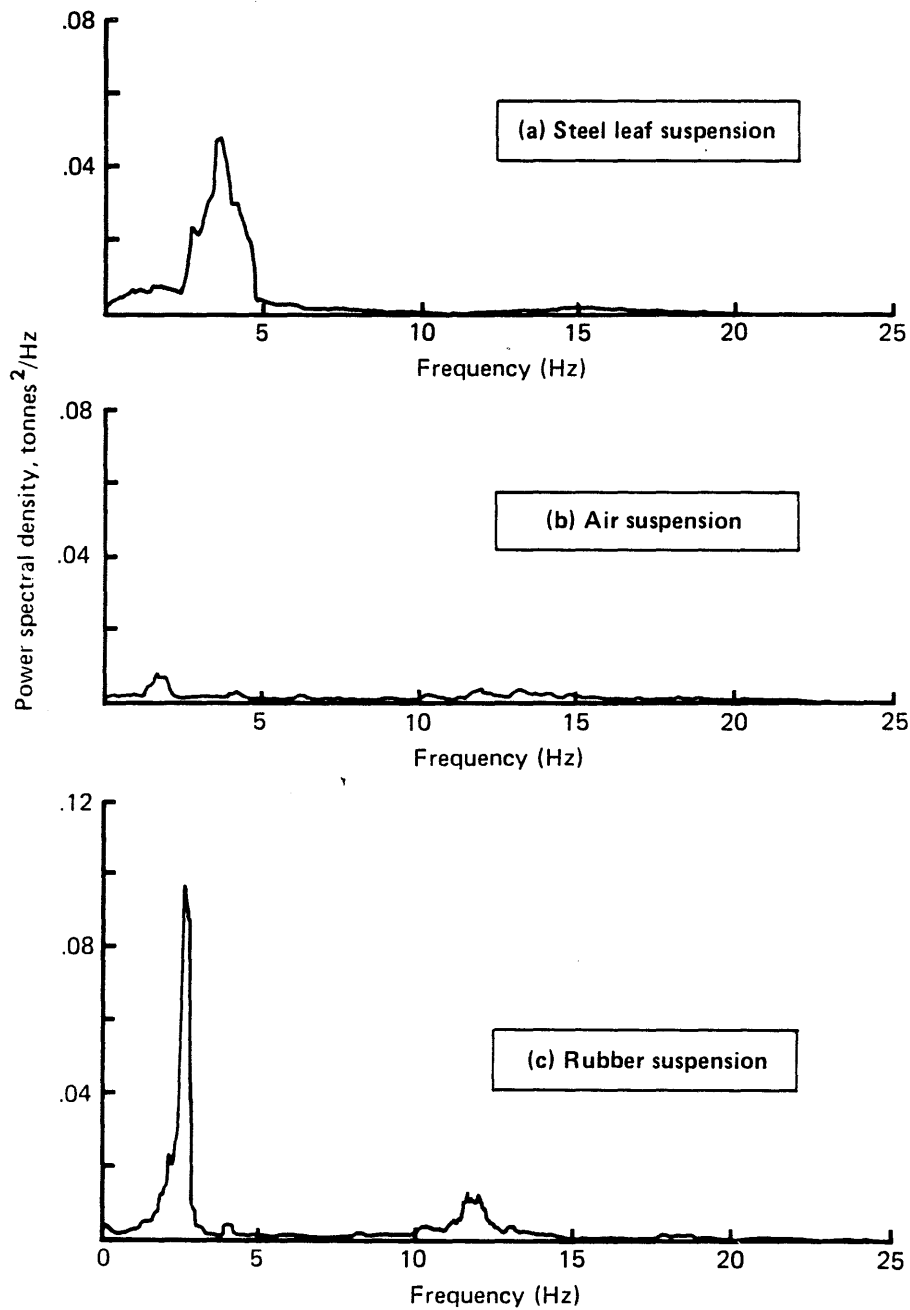Vehicles fully loaded

Fig.3 Dynamic load coefficients for the tractor drive axle and 2-and 3-axle semi-trailer bogies on the medium section of the TRRL track. Vehicles fully loaded

Fig.4 Dynamic load coefficients for the tractor drive axle and 2-and 3-axle
semi-trailer bogies on the smooth section of the TRRL track.
Vehicles fully loaded

Fig.5 Power spectral densities of the dynamic wheel loads for three semi-trailer bogies at 48km/h on the medium roughness section of the TRRL track
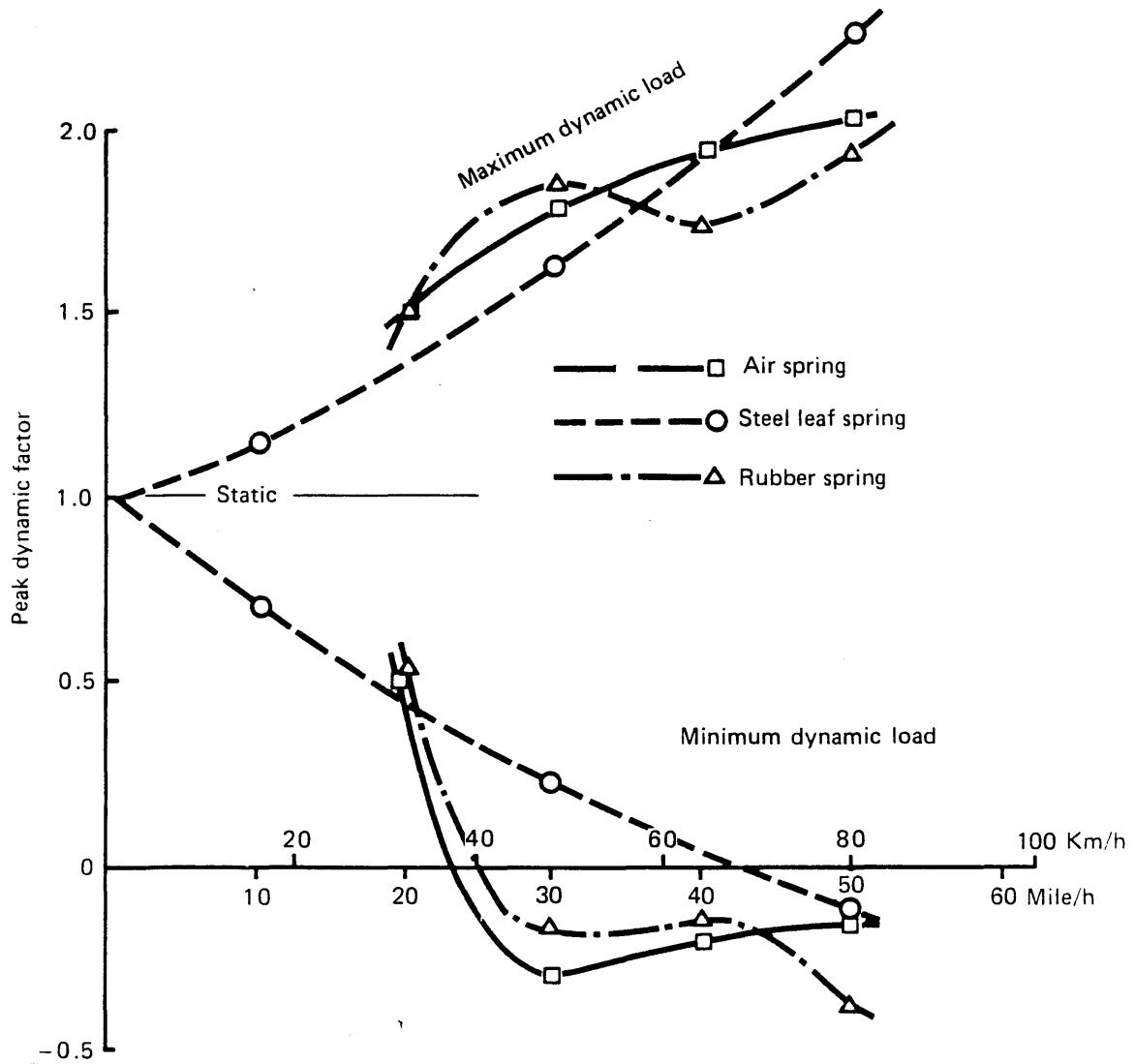
Fig.6 Peak transient dynamic factors for three semi-trailer bogies crossing a 25mm plank on the TRRL track
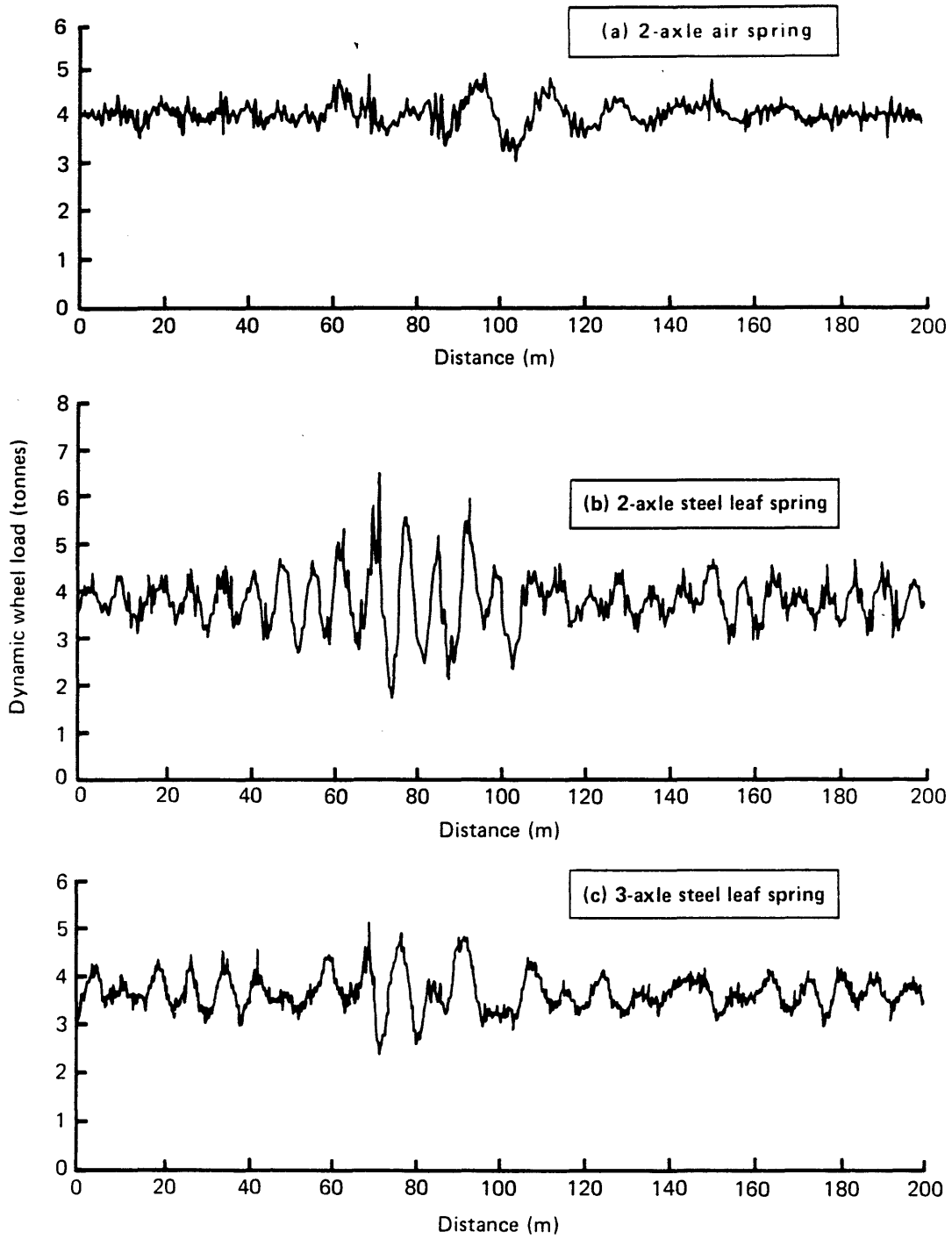
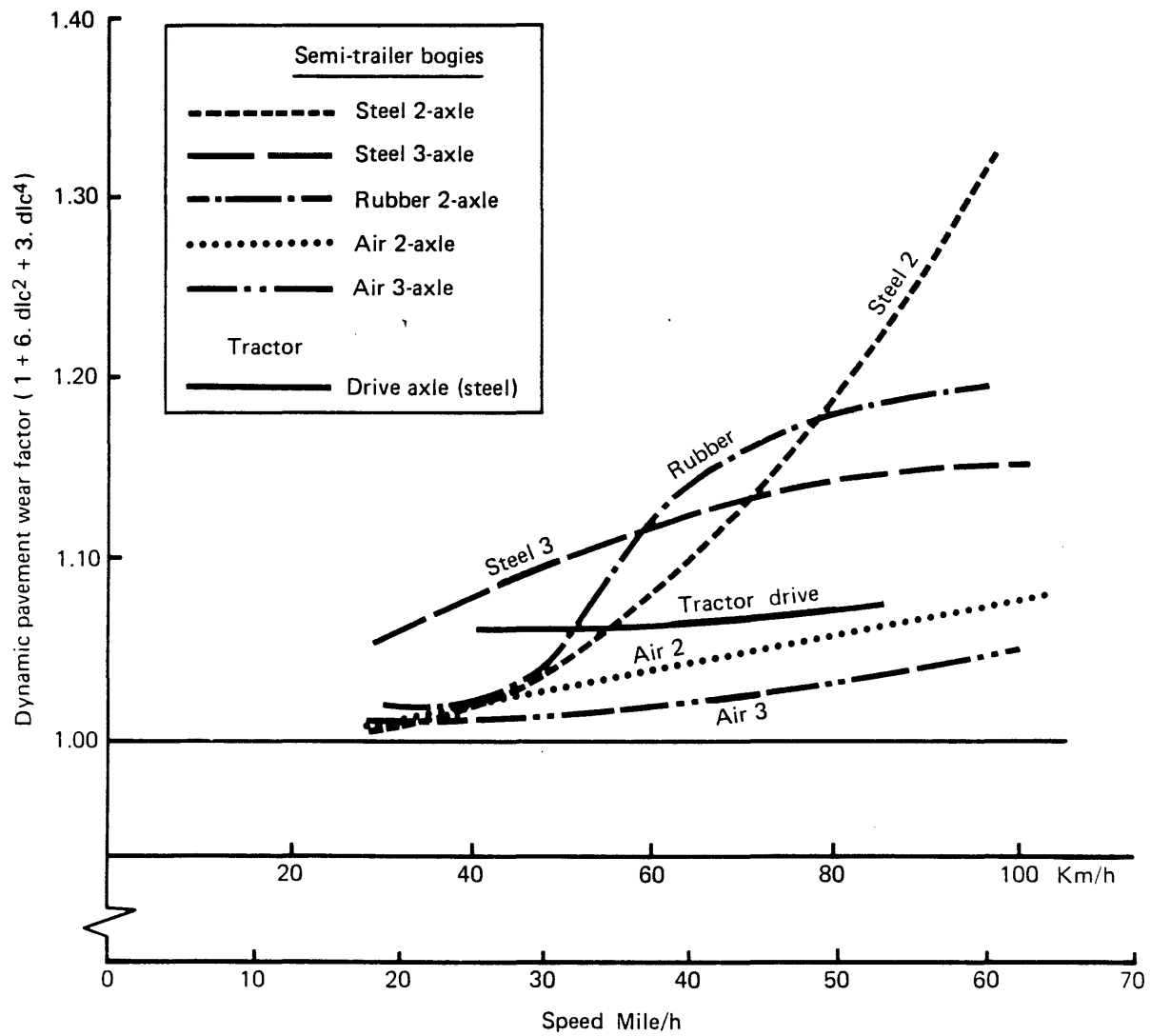Fig.7 Dynamic wheel loads for three semi-trailer bogies at 80km/h on a motorway bridge

Fig.8 Dynamic pavement wear factor for various suspensions on the medium section of the TRRL track. Vehicles fully loaded